Ultra High Energy Neutrino Signature in Top-Down Scenario

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Abstract

Neutrinos are the best candidates to test the extreme Universe and ideas beyond the Standard Model of particle Physics. Once produced, neutrinos do not suffer any kind of attenuation by intervening radiation fields like the Cosmic Microwave Background and are not affected by magnetic fields. In this sense neutrinos are useful messengers from the far and young Universe. In the present paper we will discuss a particular class of sources of Ultra High Energy Cosmic Rays introduced to explain the possible excess of events with energy larger than the Graisen-Zatsepin-Kuzmin cut-off. These sources, collectively called top-down, share a common feature: UHE particles are produced in the decay or annihilation of superheavy, exotic, particles. As we will review in the present paper, the largest fraction of Ultra High Energy particles produced in the top-down scenario are neutrinos. The study of these radiation offers us a unique opportunity to test the exotic mechanisms of the top-down scenario.

1. Introduction

The Ultra High Energy (UHE) neutrino detection is one the most important step forward in the Cosmic Ray (CR) Physics. The discovery of neutrinos with energy larger than 10^{17} eV will start the neutrino astronomy, enabling the observation of the most distant and powerful sources in the Universe. The existence of neutrinos with such high energy is intimately related to the observation of Ultra High Energy Cosmic Rays (UHECR).

Soon after the discovery of the Cosmic Microwave Background (CMB) radiation it was shown that the flux of UHECR, with an energy larger than 10^{18} eV, should be characterized by a sharp steepening at energies $\sim 10^{20}$ eV, due to the absorption processes on the CMB radiation. This effect is the well known Graisen-Zatsepin-Kuzmin (GZK) cut-off [1]. After a few decades of observations the detection of the GZK steepening is still one of the major open problems in UHECR physics and the experimental data are not conclusive. The 11 Akeno Grand Air Shower Array (AGASA) events with energy larger than 10^{20} eV [2] contradict the expected suppression of the UHECR spectrum. On the other hand the HiRes data seem to be consistent with the GZK cut-off picture [2]. If the UHECR primaries are protons and if they propagate rectilinearly, as the claimed correlation with BL-Lacs at energy $4-8\times10^{19}$ eV implies [3], than their sources must be seen in the direction of the highest energies events with energies up to $2-3\times10^{20}$ eV detected by HiRes, Fly's Eye and AGASA [2]. At these energies the proton attenuation length is only about $20-30$ Mpc and no counterparts in any frequency band was observed in the direction of these UHECR events. This is a strong indication that CR particles with energies larger than 10^{20} eV may have a different origin from those with lower energies.

Models of origin of UHECR fall into two categories, top-down and bottom-up. In the bottom-up scenario UHECR originates from cosmic accelerators. In these accelerators particles of relatively low energy are brought to UHE through multiple interactions at the source. The most promising accelerators known in nature are based on the diffusive shock acceleration mechanism, in which the particle acceleration is realized through multiple interactions with a shock front. This mechanism works fairly well in Super Nova Remnants (SNR) that are believed to be the responsible for the acceleration of Galactic Cosmic Rays of energy $E < 10^{18}$ eV (for a review see [4]). At the highest energies different bottom-up scenario have been proposed, among them, the most promising, are those in which acceleration is realized through the interaction with a relativistic shock front in Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB). In the framework of bottom-up models the observed UHECR flux should show the predicted GZK steepening and UHE neutrinos are produced by the interaction of UHECR with different backgrounds, at the source and during their journey to us. These are the so-called cosmogenic neutrinos (first proposed in [5]) that we will not discuss here.

The presence of an excess of events as claimed by AGASA inspired the introduction of several exotic models for the production of UHECR. These models, collectively called top-down, explain the excess of AGASA and give also a clear explanation for the lacking of any counterpart of the highest energy events. Many different ideas have been proposed among top-down models: strongly interacting neutrinos [6] and new light hadrons [7] as unabsorbed signal carriers, Z-bursts [8], Lorentz-invariance violation [9], Topological Defects (TD) (see [10] for a review), and Superheavy Dark Matter (SHDM) (see [11] for a review).

In the present paper we will concentrate our attention on the two last models that show common features: UHE particles are produced in the decay of superheavy particles, that we shall call collectively X particles, with a typical mass of the order of the Grand Unified energy scale $M_{GUT} \simeq 10^{24}$ eV. In the case of TD the X particle once produced, by the internal dynamics of the defect or through the interaction of different defects, immediately decays. While in the case of SHDM the X particle itself is long-lived contributing to the Dark Matter of the universe.

From the point of view of elementary particle physics the X particle decay process proceed in a way similar to e^+e^- annihilation into hadrons: two or more off-mass-shell quarks and gluons are produced and they initiate a QCD cascade. Finally the partons are hadronized at the confinement radius. Most of the hadrons in the final state are pions and thus the typical prediction of all these models is the dominance of neutrinos and photons at the highest energies $E \geq 5 \times 10^{19}$ eV. It is important to stress here that these models predict neutrino fluxes most likely within reach of the first generation neutrino telescopes such as AMANDA, and certainly detectable by future kilometer-scale neutrino observatories [12].

2. Hadrons spectrum in X decay

The first step to determine the neutrino flux produced in the decay of X particles is the determination of the hadron spectrum. Moreover, this evaluation is particularly important because it represents a direct signature of the production mechanism that, in principle, can be detected experimentally. As discussed in the introduction, the mass of the decaying particle, M_X, that represents the total CMS energy $\sqrt{s}$, is in the range $10^{13} - 10^{16}$ GeV.

The existing QCD Monte Carlo (MC) codes become numerically unstable at much smaller energies, e.g., at $\sqrt{s} \sim 10^7$ GeV and the computing time increases rapidly going to larger energies. In this section we will briefly review the main results obtained, in the computation of the top-down spectrum of UHE particles, using two different computational techniques: one based on a new MC scheme [13,14] and the other based on the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [13,16]. In both cases SUSY is included in the computation.

Monte Carlo simulations are the most physical approach for high energy calculations which allow to incorporate many important physical features as the presence of SUSY partons in the cascade and coherent branching. The perturbative part of a QCD Monte Carlo simulation is quite standard with the inclusion of SUSY. For the non-perturbative hadronization part an original phenomenological approach is used in Ref. [13]. The fragmentation of a parton i into an hadron h is expressed through perturbative fragmentation function of partons $D_i^j(x, M_X)$, that represents the probability of fragmentation of a parton i into a parton j with momentum fraction $x = 2p/M_X$, convoluted with the hadronization functions $f_j^h(x, Q_0)$ at scale Q_0, that is understood as the fragmentation function of the parton i into the hadron h at the hadronization scale $Q_0 \simeq 1.4$ GeV [13]. To obtain the fragmentation functions of hadrons one has:

$$D_i^h(x, M_X) = \sum_{j=q,g} \int_x^1 \frac{dz}{z} D_i^j(\frac{x}{z}, M_X) f_j^h(z, Q_0) \tag{1}$$

where the hadronization functions do not depend on the scale M_X. This important property of hadronization functions allows the determination of $f_i^h(x, Q_0)$ from the available LEP data, $D_i^h(x, M_X)$ at the scale $M_X = M_Z$.

The fragmentation functions $D_i^h(x, M_X)$ at a high scale M_X can be calculated also evolving them from a low scale, e.g. $M_X = M_Z$, where they are known experimentally or with great accuracy using the MC scheme. This evolution is described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation [15] which can be written as

$$\partial_t D_i^h = \sum_j \frac{\alpha_s(t)}{2\pi} P_{ij}(z) \otimes D_j^h(x/z, t)\,, \tag{2}$$

where $t = \ln(s/s_0)$ is the scale, $\otimes$ denotes the convolution $f \otimes g = \int_z^1 dx/x f(x) g(x/z)$, and P_{ij} is the splitting function which describes the emission of parton j by parton i. Apart from the experimentally rather well determined quark fragmentation function $D_q^h(x, M_Z)$, also the gluon fragmentation function $D_g^h(x, M_Z)$ is needed for the evolution of Eq. (2). The gluon FF can be taken either from MC simulations or from fits to experimental data, in particular to the longitudinal polarized e^+e^- annihilation cross-section and three-jet events. The first application of the DGLAP method for the calculation of hadron spectra from decaying superheavy particles has been made in Refs. [16]. The most detailed calculations have been performed by Barbot and Drees [16], where more than 30 different particles were allowed to be cascading and the mass spectrum of the SUSY particles was taken into account. The results obtained with the two different techniques discussed above agree fairly well [13]. The accuracy in the hadron spectrum calculations has reached such a level that one can consider the spectral shape as a signature of the model. The predicted hadron spectrum is approximately $\propto dE/E^{1.9}$ in the region of x relevant for UHECR observations.

3. Spectra of Neutrinos, Photons and Nucleons

The spectra of neutrinos and photons produced by the decay of superheavy particles are of practical interest in high energy astrophysics and can be computed from the decay of charged pions [13]. The FFs for charged pions and protons+antiprotons can be determined, following [13], from the FFs of hadrons D_h simply introducing the ratios $\varepsilon_N(x)$ and $\varepsilon_\pi(x)$ as: $D_N(x) = \varepsilon_N(x)D_h(x)$ and $D_\pi(x) = \varepsilon_\pi(x)D_h(x)$. The spectra of pions and nucleons at large M_X have approximately the same shape as the hadron spectra, and one can use in this case $\varepsilon_\pi = 0.73 \pm 0.03$ and $\varepsilon_N = 0.12 \pm 0.02$ [13].

An interesting feature of the up-dated calculations performed in [13] and by Barbot and Drees in [16] is the ratio of photons to nucleons, γ/N. At $x \sim 1 \times 10^{-3}$ this ratio is characterized by a value of $2-3$ only [13]. This result has an important impact for SHDM and topological defect models because the fraction of nucleons in the primary radiation increases. However, in both models photons dominate (i.e. their fraction becomes $\geq 50\%$) at $E \geq (7-8) \times 10^{19}$ eV.

Let us now concentrate our attention on UHECR from superheavy dark matter (SHDM) [18] and topological defects (TD) [19]. The comparison of the UHECR spectrum obtained with the AGASA data, will provide us with the correct neutrino flux normalization.

Production of SHDM particles naturally occurs in a time-varying gravitational field of the expanding universe at the post-inflationary stage. The relic density of these particles is mainly determined (at fixed reheating temperature and inflaton mass) by their mass M_X. The range of practical interest is $(3-10) \times 10^{13}$ GeV, at larger masses the SHDM is a subdominant component of the DM. SHDM is accumulated in the Galactic halo with the overdensity $\delta = \frac{\bar{\rho}_X^{\rm halo}}{\rho_X^{\rm extr}} = \frac{\bar{\rho}_{\rm DM}^{\rm halo}}{\Omega_{\rm CDM}\rho_{\rm cr}}$, where $\bar{\rho}_{\rm DM}^{\rm halo} \approx 0.3$ GeV/cm^3, $\rho_{\rm cr} = 1.88 \times 10^{-29} h^2$ g/cm^3 and $\Omega_{\rm CDM}h^2 = 0.135$ [20]. With these numbers, $\delta \approx 2.1 \times 10^5$. Because of this large local overdensity, UHECRs from SHDM have no GZK cutoff.

Clumpiness of SHDM in the halo can provide the observed small-angle clustering. The ratio $r_X = \Omega_X(t_0/\tau_X)$ of relic abundance Ω_X and lifetime τ_X of the X particle is fixed by the observed UHECR flux as $r_X \sim 10^{-11}$. In the most interesting case of gravitational production of X particles, their present abundance is determined by their mass M_X and the reheating temperature T_R. Choosing a specific particle physics model one can fix also the life-time of the X particle. There exist many models in which SH particles can be quasi-stable with lifetime $\tau_X \gg 10^{10}$ yr. The measurement of the UHECR flux, and thereby of r_X, selects from the three-dimensional parameter space (M_X, T_R, τ_X) a two-dimensional subspace compatible with the SHDM hypothesis.

In Figure 1 (left panel) we have performed a fit to the AGASA data using the photon flux from the SHDM model and the proton flux from uniformly distributed astrophysical sources. For the latter we have used the non-evolutionary model of [21]. The photon flux is normalized to provide the best fit to the AGASA data at $E \geq 4 \times 10^{19}$ eV.

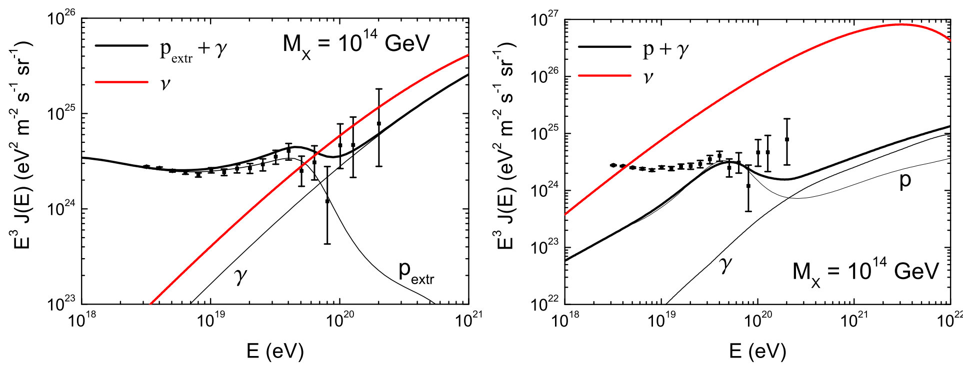

Fig. 1. [Right Panel] Comparison of SHDM prediction with the AGASA data. The calculated spectrum of SHDM photons is shown by the label γ and by the label p_{extr} the spectrum of extragalactic protons (uniformly distributed astrophysical sources). The sum of these two spectra is shown by the thick black curve. The red thick line is the SHDM neutrino flux. [Left Panel] Diffuse spectra from necklaces. The red thick curve shows neutrino flux, the black thick curve is the sum of protons and photons fluxes produced by necklaces (labeled thin black lines).

One can see from the fit of Figure 1 (left panel), that the SHDM model can explain only the excess of AGASA events at $E \geq 1 \times 10^{20}$ eV: depending on the SHDM spectrum normalization and the details of the calculations for the extragalactic protons, the flux from SHDM decays becomes dominant only above $(6-8) \times 10^{19}$ eV.

Topological Defects (for a review see [22] and reference therein) can naturally produce UHE particles. The following TD have been discussed as potential sources of UHE particles: superconducting strings, ordinary strings, monopolonium (bound monopole-antimonopole pair), monopolonia (monopole-antimonopole pairs connected by a string), networks of monopoles connected by strings, vortons and necklaces (see Ref. [22] for a review and references). Monopolonia and vortons are clustering in the Galactic halo and their observational signatures for UHECR are identical to SHDM. However the friction of monopolonia in cosmic plasma results in monopolonium lifetime much shorter than the age of the universe. Of all other TD which are not clustering in the Galactic halo, the most favorable for UHECR are *necklaces*.

Necklaces are hybrid TD produced in the symmetry breaking pattern $G \to H \times U(1) \to H \times Z_2$. At the first symmetry breaking monopoles are produced, at the second one each (anti-) monopole get attached to two strings. This system resembles ordinary cosmic strings with monopoles playing the role of beads. Necklaces exist as the long strings and loops. The symmetry breaking scales of the two phase transitions, η_m and η_s, are the main parameters of the necklaces. They determine the monopole mass, $m \sim 4\pi\eta_m/e$, and the mass of the string per unit length $\mu \sim 2\pi\eta_s^2$. The evolution of necklaces is governed by the ratio $r \sim m/\mu d$, where d is the average separation of a monopole and antimonopole along the string. As it is argued in Ref. [23], necklaces evolve towards configuration with $r \gg 1$. Monopoles and antimonopoles trapped in the necklaces inevitably annihilate in the end, producing heavy Higgs and gauge bosons (X particles) and then hadrons. The rate of X particles production in the universe can be estimated as [23] $\dot{n}_X \sim \frac{r^2 \mu}{t^3 M_X}$, where t is the cosmological time.

The photons and electrons from pion decays initiate e-m cascades and the cascade energy density can be calculated as $\omega_{\rm cas} = \frac{1}{2} f_\pi r^2 \mu \int_0^{t_0} \frac{dt}{t^3} \frac{1}{(1+z)^4} = \frac{3}{4} f_\pi r^2 \frac{\mu}{t_0^2}$, where

z is the redshift and $f_\pi \sim 1$ is the fraction of the total energy release transferred to the cascade. The parameters of the necklace model for UHECR are restricted by the EGRET observations [24] of the diffuse gamma-ray flux. This flux is produced by UHE electrons and photons from necklaces due to e-m cascades initiated in collisions with CMB photons. In the range of the EGRET observations, $10^2 - 10^5$ MeV, the predicted spectrum is $\propto E^{-\alpha}$ with $\alpha = 2$ [25]. The EGRET observations determined the spectral index as $\alpha = 2.10 \pm 0.03$ and the energy density of radiation as $\omega_{\rm obs} \approx 4 \times 10^{-6}$ eV/cm^3. The cascade limit consists in the bound $\omega_{\rm cas} \leq \omega_{\rm obs}$. According to the recent calculations, the Galactic contribution of gamma rays to the EGRET observations is larger than estimated earlier, and the extragalactic gamma-ray spectrum is not described by a power-law with $\alpha = 2.1$. In this case, the limit on the cascade radiation with $\alpha = 2$ is more restrictive and is given by $\omega_{\rm cas} \leq 2 \times 10^{-6}$eV/cm^3; we shall use this limit in further estimates. Using $\omega_{\rm cas}$ with $f_\pi = 1$ and $t_0 = 13.7$ Gyr [20] we obtain from the limit on the cascade radiation $r^2\mu \leq 8.9 \times 10^{27}$ GeV^2.

The important and unique feature of necklaces is their small separation D, which ensures an high density. The distance D is given by $D \sim r^{-1/2} t_0$ [23]; since $r^2\mu$ is limited by e-m cascade radiation we can obtain a lower limit on the separation between necklaces as $D \sim \left(\frac{3 f_\pi \mu}{4 t_0^2 \omega_{\rm cas}}\right)^{1/4} t_0 > 10(\mu/10^6 \text{ GeV}^2)^{1/4}$ kpc, this small distance is a unique property of necklaces allowing the unabsorbed arrival of particles with the highest energies. The fluxes of UHECR from necklaces are shown in Figure 1 (right panel). We used in the calculations $r^2\mu = 4.7 \times 10^{27}$ GeV^2 which corresponds to $\omega_{\rm cas} = 1.1 \times 10^{-6}$ eV/cm^3, i.e. twice less than allowed by the bound on $\omega_{\rm cas}$. The mass of the X particles produced by monopole-antimonopole annihilations is taken as $M_X = 1 \times 10^{14}$ GeV. From Figure 1 (right panel) one can see that the necklaces model for UHECR can explain only the highest energy part of the spectrum, with the AGASA excess somewhat above the prediction. Thus UHE particles from necklaces can serve only as an additional component in the observed UHECR flux. This result has a particular impact on the possible UHE neutrino detection. In fact, the necklaces model is only under constrained by the available UHECR data, in this context only a clear UHE neutrino observation with a typical spectrum as in figure 1 (right panel) can confirm (or falsify) the model.

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